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SECONDARY COMBUSTION OF PENTABORANE-HYDRAZINE EXHAUST IN AIR

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TECHNICAL REPORT AFRPL-TR-67-242

August 1967

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AIR FORCE ROCKET PROPULSION LABORATORY
Research and Technology Division
Air Force Systems Command
United States Air Force
Edwards, California

NOTICES

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FOREWORD

This progress report (Aerojet Report No. 1134-81-1), covering the period from 1 May through 31 July 1967, is submitted in partial fulfillment of Contract F04611-67-C-0106.

This investigation is being conducted by the Fuels and Combustion Research Section of the Advanced Propulsion Research Department, Research and Technology Operations, Aerojet-General Corporation, Sacramento, California. The Air Force monitor for the program is A. McPeak, Lt., USAF/RPCL.

The work described herein was performed by S. D. Rosenberg, R. E. Yates and R. C. Adrian. This report was written by the program staff.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

ABSTRACT

The design of the first of two liquid micromotors has been completed. This micromotor will be used for the determination of characteristic velocity and chamber temperature and for analysis of the exhaust products. The preparation of the test site has begun and the fabrication and installation of the micromotor and auxiliary equipment have been initiated.

A tentative test plan has been developed for the study of the combustion characteristics in air of the exhaust products of the pentaborane-hydrazine system.

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SECTION I

INTRODUCTION

Air-augmented rockets offer significant improvement in specific impulse over conventional rockets. The improvement is realized through two important mechanisms: first, through addition of the air mass to the exhaust stream and, second, by achieving additional combustion of the primary rocket exhaust when the primary rocket is operated in an under-oxidized condition. Therefore, primary propellant systems which produce exhaust products that may be oxidized further in air are attractive for air-augmentation applications.

The pentaborane-hydrazine propellant system is especially attractive in that the exhaust of this system consists chiefly of hydrogen, boron nitride, and boron. If significant combustion of these exhaust products can be achieved in air, a system of exceptional performance may be realized.

The objective of this program is to establish the combustion characteristics in air of the exhaust products of the pentaborane-hydrazine system. A study of the combustion will be conducted using two liquid micromotors. The test variables which will be investigated include the following:

1. Temperature and pressure of the secondary air, simulating both low altitude/moderate Mach number, 2.5, and high altitude/high Mach number, 4.0.

2. Air-to-propellant-weight flow ratios in the range 8:1 to 40:1.

3. Primary propellant mixture ratios (N_2H_4/B_5H_9) in the range 1.27 to 0.6.

4. Secondary combustion chambers (not more than three) of different diameters and lengths.

5. Composition of secondary air, i.e., air or nitrogen.

Test measurements which will be required include the following:

1. Propellant and air flow rates.

2. Air inlet temperature and pressure.

3. Primary and secondary chamber pressures.

4. Total thrust.

5. The extent of conversion of the boron nitride and boron to boron oxides, by collection and analysis of the exhaust products.

I, Introduction (cont.)

      6.   Spectral gas-temperature and other optical measurements in the secondary chamber.

Characteristic velocity, chamber temperature and specific impulse will be calculated based on these test measurements, and a combustion model will be developed.

SECTION II

SUMMARY

The technical effort on this program is divided into three distinct phases. The work accomplished on each of these phases during the first quarter of the program are reported below.

A. PHASE I: DESIGN, FABRICATION, AND INSTALLATION OF
    MICROMOTOR FACILITIES

    1. Micromotor "A"

        The site selected for the experimental test program is in the Research Physics Laboratory of the Advanced Propulsion Research Department. The test bay and auxiliary facilities are being installed currently.

        The designs of the air-heating system and the combustor components have been completed. Fabrication and installation of the air-heater are in progress. Fabrication of the combustor components is currently underway. These components include the primary propellant and igniter injectors, the water-cooled primary combustion chamber and nozzle, the augmenting-air injector, the water-cooled secondary chamber and replaceable nozzles.

    2. Exhaust Sampling System

        The design of the exhaust sampling system is nearing completion. The exhaust duct, with provision for liquid-argon injection and exhaust sampling, is currently being fabricated. The design of the dust-collector is under consideration.

    3. Spectral Equipment

        The assembly of the equipment for spectral temperature determination is almost complete. Modifications of existing equipment and the fabrication of additional components are complete with two exceptions: the light-source intensity monitors and the ring mounting which supports the light-sources.

        The complex refractive index of BN, required for particle-cloud temperature determination, has been obtained from data supplied by Dr. W. W. Lozier and by N. J. Norante.

        A computer program for the determination of temperatures from the spectral data has been developed.

II, A, Phase I: Design, Fabrication, and Installation of
Micromotor Facilities (cont.)

4. Micromotor "B"

The thrust combustor is not scheduled for use until later in
the program. Acquisition of materials and components for the thrust combustor
and stand has been initiated.

B. PHASE II: DETERMINATION OF COMBUSTION CHARACTERISTICS IN AIR OF EXHAUST PRODUCTS OF PENTABORANE-HYDRAZINE SYSTEM

Phase II is concerned with the engine test evaluation of the air-
augmented pentaborane-hydrazine system. A tentative test plan has been
developed to provide the requisite data. Fifty-two tests are planned with
Micromotor A. In the course of these tests, the temperature profile in the
secondary chamber will be measured, the exhaust products will be analyzed, and
the characteristic velocity will be determined under a variety of conditions.

Micromotor B will be used to conduct 23 tests under similar condi-
tions to determine the total thrust and specific impulse. Characteristic
velocities will be determined for comparison with the Micromotor A results.

C. PHASE III: INTERPRETATION OF MICROMOTOR TEST RESULTS

Phase III is concerned with the development of a theoretical model
of the combustion process or processes. Correlation between the various
experimental parameters will be sought through theoretical chemical and physical
considerations.

SECTION III

TECHNICAL DISCUSSION

The program is divided into three phases: Phase I, Design, Fabrication, and Installation of Laboratory Micromotor Facilities; Phase II, Determination of the Combustion Characteristics in Air of the Exhaust Products from the Pentaborane-Hydrazine System; and Phase III, Interpretation of Micromotor Test Results. The work accomplished during the period 1 May to 31 July 1967 is discussed below.

A. PHASE I: DESIGN, FABRICATION, AND INSTALLATION OF LABORATORY MICROMOTOR FACILITIES

Phase I is concerned with the design, fabrication, and installation of two liquid micromotors, "A" and "B." Micromotor A will be used for the determination of characteristic velocity, c^*; for the determination of exhaust product composition, both gaseous and solid; and for the measurement of gas and particle temperatures in the secondary chamber. Micromotor B will be used for the measurement of total thrust and for the determination of characteristic velocity and specific impulse, I_{sp}.

1. Test Site

The test site for the experimental combustion studies is in the Research Physics Laboratory of the Advanced Propulsion Research Department. The test bay is being prepared for the installation of Micromotor A. The stand to be used to support the combustor and auxiliary apparatus is currently being modified.

2. Secondary-Air Heating System

Careful consideration has been given to the design of the secondary-air heating system. The use of a pebble-bed heat exchanger, preheated by means of the combustion of LPG-air, was originally suggested for this purpose. However, the large power supply (400 kw) available in the Research Physics Laboratory is adequate to preheat the augmenting air required by the test program. Therefore, an electrical heating system has been designed and is being constructed and installed in the test bay. A schematic of the heater is shown in Figure 1.

An analysis of the electrical heating system was made and the following conclusions were reached:

a. 400 kw will provide 22,768 Btu/min. This is sufficient energy to bring 1.0 lb/sec of air to 1477°F from 50°F or to raise 1.355 lb air/sec through a ΔT of 1180°F. Maximum required conditions may be reached by preheating the air reservoir to a temperature of 320°F.

III, A, Phase I: Design Fabrication, and Installation of Laboratory
Micromotor Facilities (cont.)
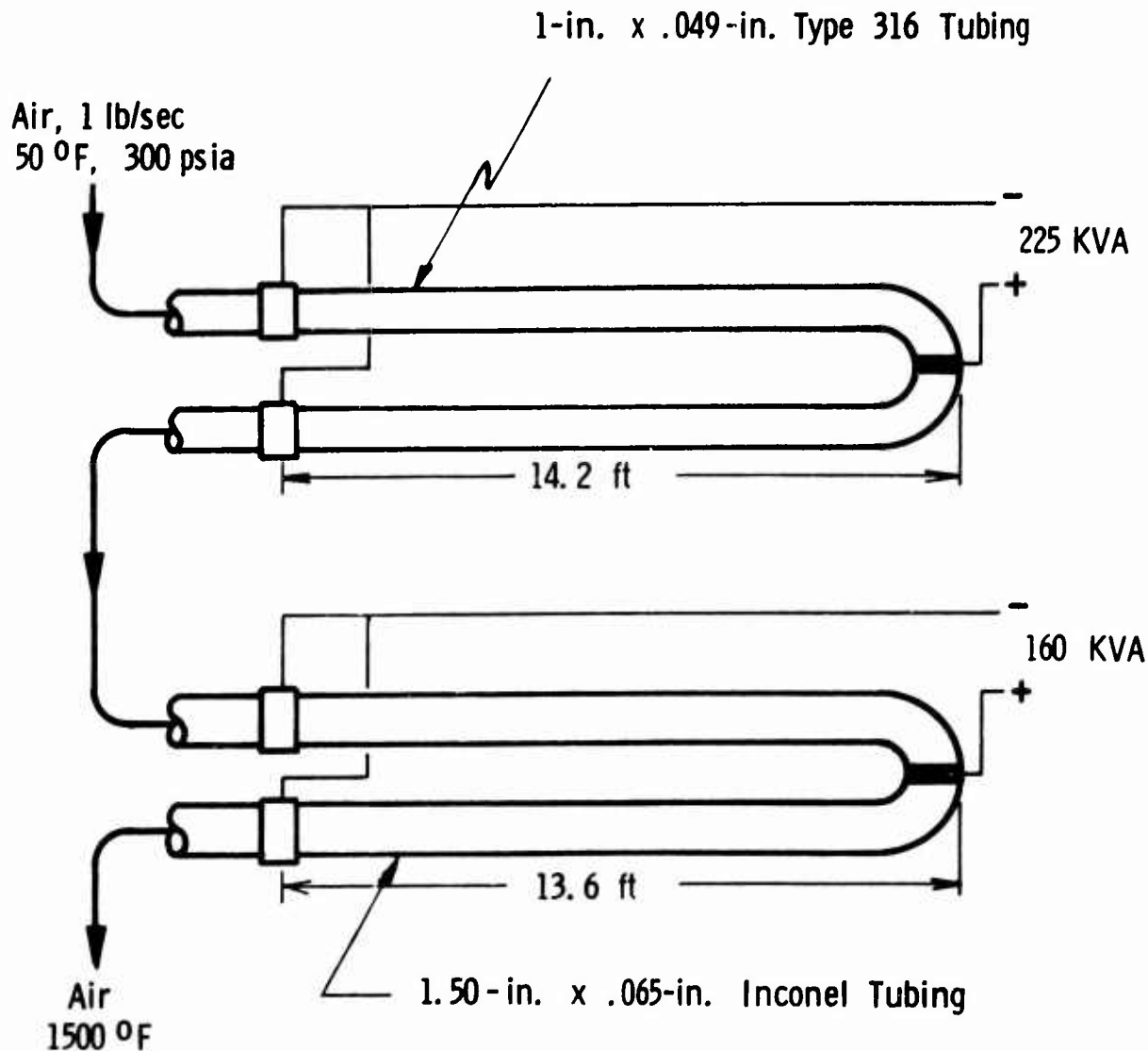
FIGURE 1.   SCHEMATIC OF AIR HEATER

        b.   Pressure drop through the tubing will be less than
40 psi at the high air velocities required, 225 to 500 ft/sec.

        c.   A two-increment heater will be used; the first increment
consists of 28 ft of 1-in.-dia x 0.049 Type 316 stainless steel and the second
increment consists of 27 ft of 1-1/2-in.-dia x 0.065 Inconel tubing. The
electrical properties of these tubes plus the secondary-air temperature
requirements represent power requirements of 3000 amps at 75 volts and 3000 amps
at 53 volts, respectively. Heat-transfer coefficients of the tube walls are
on the order of 200 and 155 Btu/hr ft^2, respectively.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory
          Micromotor Facilities (cont.)

          d.   Heater weight will be approximately 45 lb.

          e.   Cost may be reduced somewhat compared with the pebble-bed
heater, although the required purchase of high-temperature-resistant tubing may
offset other cost reductions.

          There are such additional benefits as the following: heating
will be instantaneous, with no hot body complicating work in the combustor
area; little or no preheat will be required; and there will be no heat limita-
tion on run duration. A high-temperature valve may not be needed; this valve
could present a major problem.

          3.   Micromotor A

          The design of the combustor components for Micromotor A has
been completed. These components include the primary propellant and igniter
injectors, the jacketed, primary combustion chamber and nozzle, augmenting-air
injector, and the jacketed, secondary combustion chamber and replaceable
nozzles. These components are being fabricated currently. A sketch of the
assembled, two-stage combustor is shown in Figure 2.
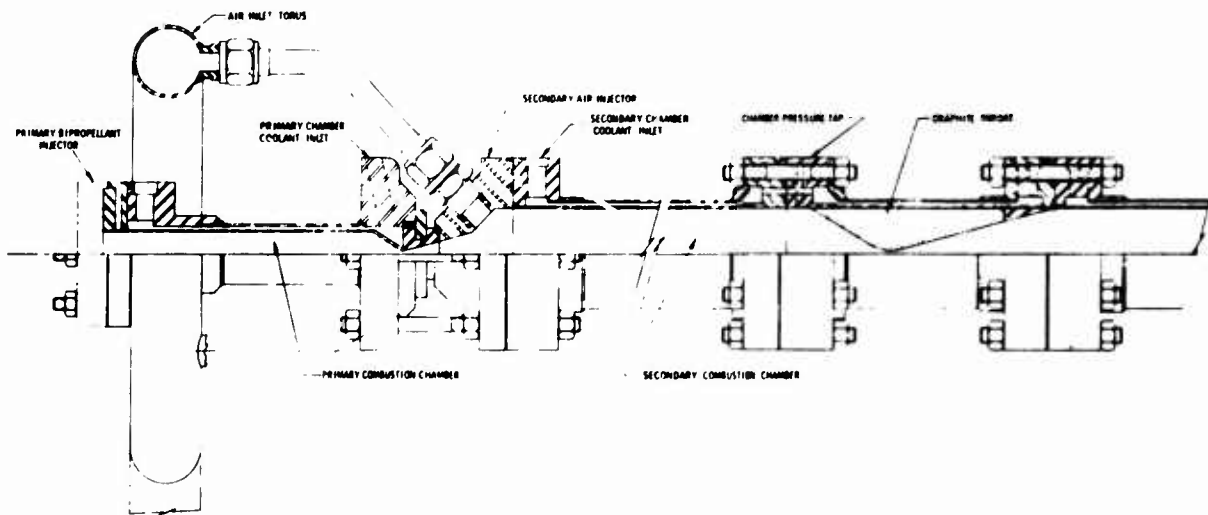
FIGURE 2.   MICROMOTOR A ENGINE ASSEMBLY, AA MOD 1

          The primary combustor is similar to the Aerojet liquid-liquid
combustor used on previous programs. The addition of the secondary chamber
plus a high degree of instrumentation make this unit substantially more complex
than those previously used, however.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory
        Micromotor Facilities (cont.)

            An uncooled injector has been designed for the primary chamber.
Initially, a modified triplet configuration fabricated from stainless steel
will be employed. A similar unit has been used previously for this bipropellant
system and provided relatively efficient combustion. A pentad spray injector
will be used as a backup unit. Ignition will be achieved by means of a time-
sequenced injection of a liquid oxidizer, i.e., N_2O_4, because the basic bipro-
pellant combination is not hypergolic.

            The primary chamber is approximately 6 in. long (injector to
throat) and 0.90 in. in diameter. The stainless steel nozzle (0.125-in.-dia
throat) and the primary chamber are enclosed within a water-cooling jacket
which will provide heat loss data.

            Air flow to the secondary chamber will be controlled by a
sonic nozzle ahead of a toroid manifold. Three tubes connect the manifold to
replaceable nozzles in the air injector. The nozzles will be selected to pro-
vide an inlet velocity of Mach 0.4.

            The secondary chamber, shown simply as a jacketed tube in
Figure 2, is a relatively complex component of the micromotor. Provision has
been made for a series of thermocouples along the length of the chamber to
provide temperature-profile measurements. Provision has been made also for
sets of optical windows through which the spectral temperatures will be measured.
Figure 3 is a detailed sketch showing the manner in which these ports are
assembled.
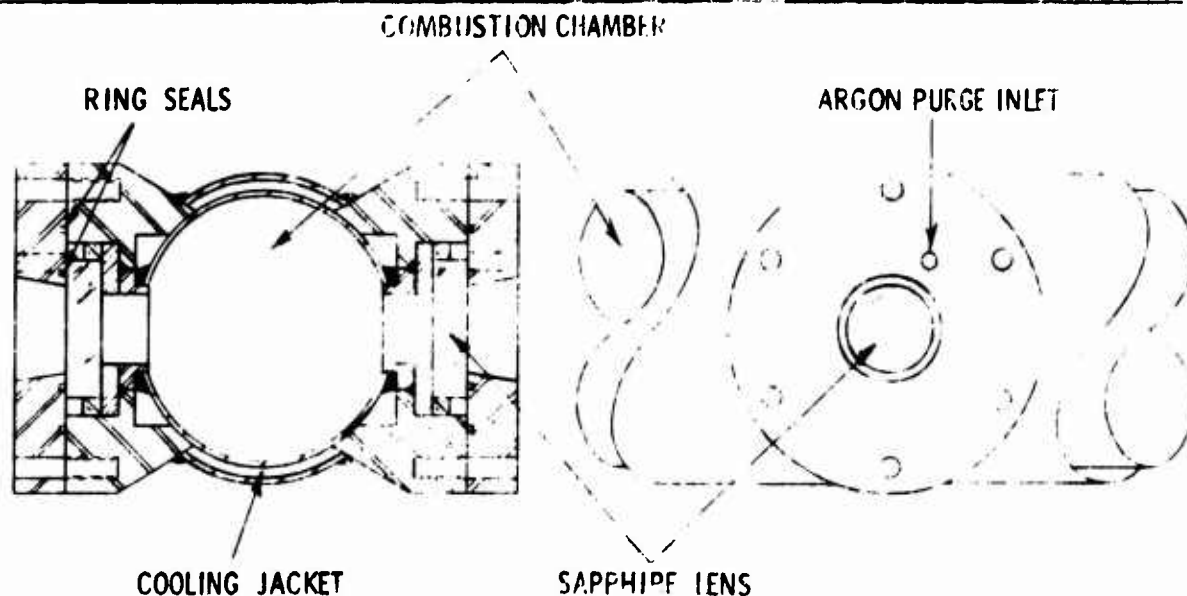
FIGURE 3. OPTICAL PORTS IN THE SECONDARY CHAMBER
        OF MICROMOTOR A

III, A, Phase I: Design, Fabrication, and Installation of Laboratory
        Micromotor Facilities (cont.)

                Replaceable graphite nozzles will be attached to the secondary
combustor tube by means of flanges. The wide range of test conditions requires
the use of several different throat areas; the use of a flanged connection
facilitates the removal of the nozzles for interchange and measurement of post-
run throat-diameters.

                Graphite has been chosen for the nozzle material because of
its superior high-temperature qualities and because its lubricity tends to
resist the adhesion of liquid and solid combustion products. In the high air-
to-propellant regime, the erosive oxidation of the nozzle may become a problem.
Should this occur, the substitution of boron nitride nozzles is expected to
eliminate the problem.

                4.   Exhaust Sampling Equipment

                The design of the exhaust sampling system is in progress
currently. The design of the exhaust duct has been completed. Figure 4 is a
sketch of the water-cooled duct showing the liquid-argon injection and exhaust
sample taps. The exhaust filtration unit is being designed at the present
time. The type of dust collection system to be used will be selected and the
appropriate equipment will be ordered.
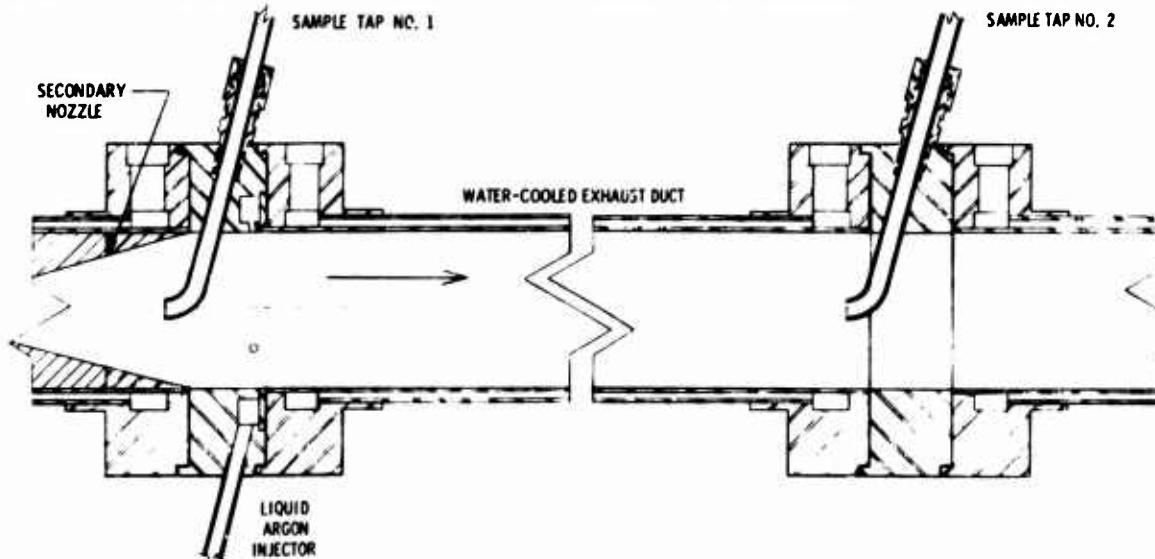
FIGURE 4.   WATER-COOLED EXHAUST DUCT

                Provision has been made for the injection, if necessary, of
liquid argon into the exhaust duct for rapid quenching of the exhaust products.
This operation is not intended for normal cooling but only to prevent post-
oxidation. The need for argon cooling will not be definitely established until
preliminary firings have been made.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory
        Micromotor Facilities (cont.)

        Auxiliary samples, taken at three different points in the
exhaust duct from the secondary nozzle, will be drawn through Millipore filters
to provide both solid and gaseous exhaust samples. These sample draw-off
operations will be timed to coincide with the main sample collection. The
occurrence of post-oxidation in the exhaust duct should become apparent from
analyses of the samples; differences in the composition of the exhaust at the
three sample-taps may be the result of post-oxidation.

        Design calculations have been made for the exhaust filtration
system. The high maximum exhaust rate, 29 cu ft/sec at 400°F, necessitates a
large filter area. Therefore, a reduction of the exhaust temperature to approxi-
mately 120 to 150°F is required to achieve a practical filter size. The exhaust
rate will vary over a wide range, and a compartmented filter may be the best
solution to this problem. The least possible collecting area is desired in
order to get more accurate material balances for the combustion experiments;
thus, the coldest practical exhaust temperature is required. A low exhaust
temperature also tends to minimize post-oxidation of the combustion products.

    5. Spectral Equipment

        The assembly of the spectral equipment is almost complete.
Modification of existing equipment and fabrication of additional components
are complete, except for the light-source intensity monitors and the ring
mounting which supports the light sources. Transport of the equipment to the
test site and installation will be undertaken as required.

        The principal objective of the spectrometric measurements is
to obtain the static gas temperature and the optical depth of the particle
cloud at three axial stations in the secondary combustor. The ultimate objec-
tive of these measurements is to infer the extent of combustion of the primary
propellant exhaust occurring at each axial station, so that the effect of
specific parameters on the overall performance of the system can be evaluated.
The progression of combustion manifests itself as a decrease in the mass
fraction of boron nitride and as an increase in the static stream temperature,
both of which can be determined from the measured values of spectral trans-
mittance* and radiance.

        The experimental program will be directed toward obtaining
(1) the spectral transmittance and radiance at the spectrum line center of the
first line of the sodium-D doublet, 5890 Å and (2) the spectral transmission
and radiance associated with the continuum emission of the particle cloud at a
wavelength of 5880 Å. These measurements will be taken at three axial stations
in the secondary combustor, across the flow centerline.

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* Words ending in -ittance refer to systems or surfaces, while words ending in
  -ivity refer to materials, following the suggestion of NBS (Reference 1).

III, A, Phase I: Design, Fabrication, and Installation of Laboratory
        Micromotor Facilities (cont.)

The principal variable of interest, the gas temperature and
its estimate of variance, will be calculated from the data taken at various
times during the firing. The optical depth of the particle cloud will be
determined from the same data. The optical depth, combined with an estimate
of the particle size distribution in the cloud, will serve to define the
condensed-phase temperature and mass fraction. From a regression analysis,
the uncertainty in both of these parameters will also be determined, based on
the uncertainty in the particle size distribution.

A requisite to the precise determination of particle tempera-
ture (but relatively unimportant to the determination of gas temperature) is
the complex refractive index of boron nitride. A literature survey was under-
taken and information requests were sent to several potential sources. A
letter and report, received from Dr. W. W. Lozier of Union Carbide Corporation,
contained optical transmission data for BN at room temperature and in the
visible region. These data, along with information supplied N. J. Norante of
the Carborundum Company, have been used to deduce the refractive index of BN
both at room temperature and at the high temperatures expected in the secondary
chamber.

The computer program employed to reduce the experimental
spectral data to the desired temperatures has been written for use on the
IBM 1130 computer. A description of the program (PROGRAM TEMP) is presented
in the Appendix of this report.

The principal part of the spectral equipment is the spectral
comparison pyrometer, which has been described in detail elsewhere
(Reference 2). The fundamental components of this device are shown in
Figure 5.
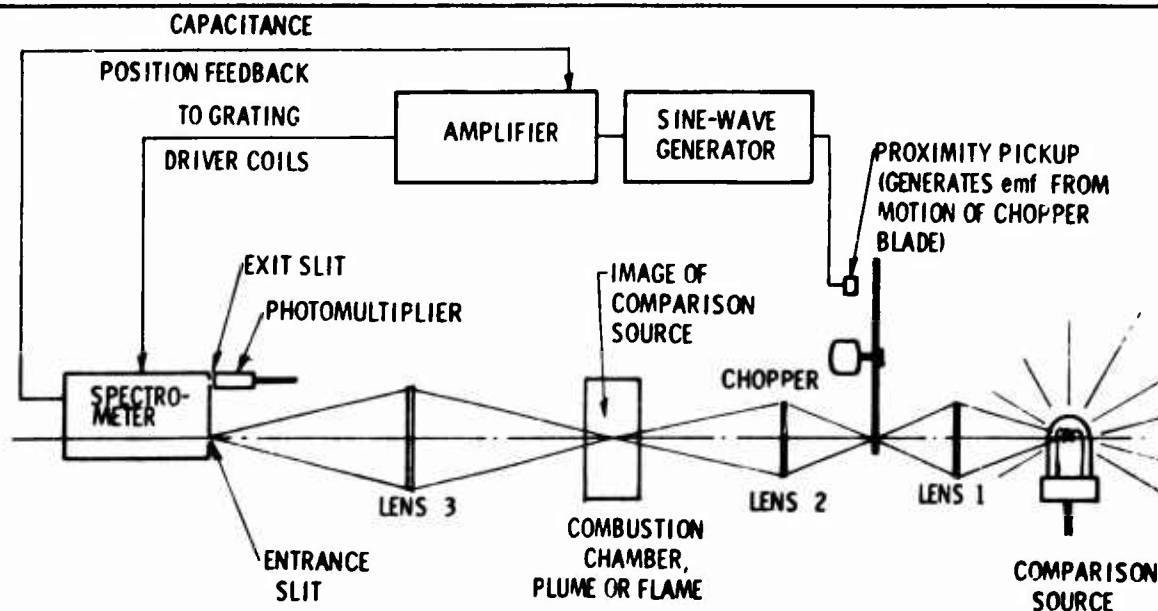
FIGURE 5.   OPTICS AND ELECTROMECHANICAL SCHEMATIC
            OF SPECTRAL COMPARISON PYROMETER

III, A, Phase I: Design, Fabrication, and Installation of Laboratory
        Micromotor Facilities (cont.)

A reference light source (DC carbon arc), chopper, and asso-
ciated optics will be used at each of the three axial positions under study.
Each of the reference source beams will pass through a set of diametrically
opposed windows. The light from each station will be picked up by an optical
light guide and passed to an optical sampling scanner which sequentially
samples the radiance from each station and focuses it on the entrance slit of
the spectrometer.
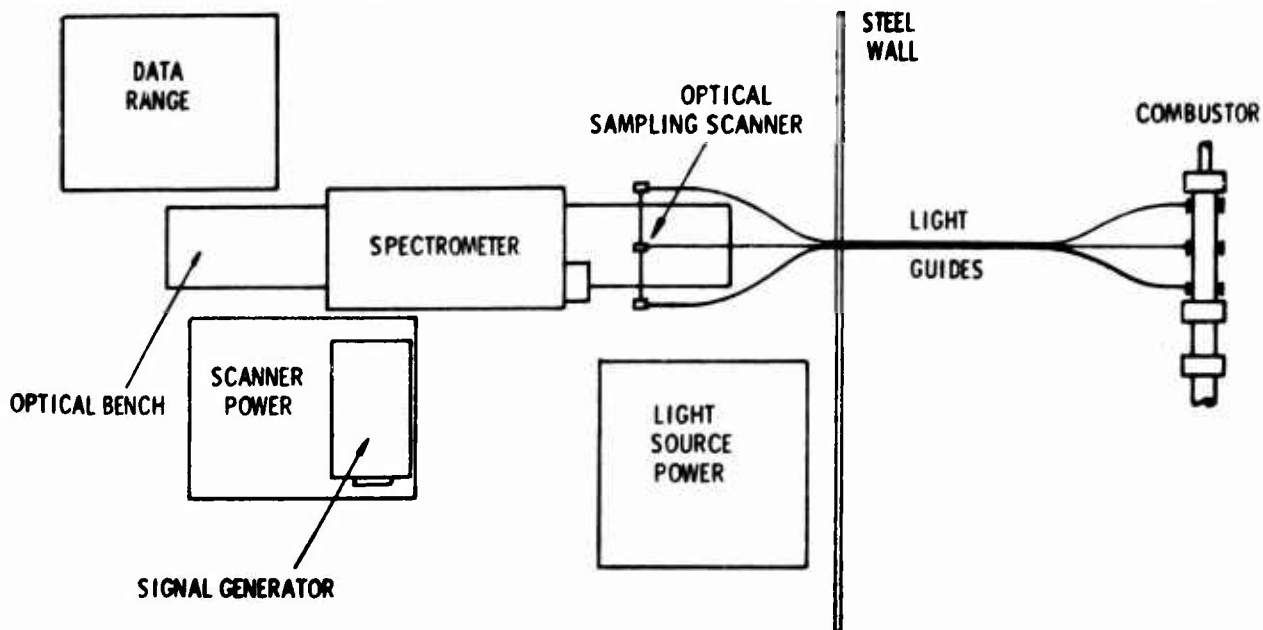
FIGURE 6. SPECTRAL EQUIPMENT LAYOUT

Placement of the apparatus is shown in Figure 6. Because of
the potential hazards associated with any engine test experiments, the
spectrometer will be protected by the steel wall shown in the figure with the
optical light guides passing through a hole in the wall. The three carbon arc
lamps and related optics will be positioned by means of mounting rings around
the secondary combustion chamber. The spectrometer and optical sampling
scanner will be placed on a lathe-bed optical bench at a distance to minimize
the length of the optical light guides.

Special components which were required to complete the
apparatus include (1) three reference source beam intensity monitors for
recording the radiance of each of the carbon arc lamps throughout a run,
(2) the scanner power supply to drive the grating within the spectrometer, and
(3) the impedance couplers and data ranging equipment to provide signals of
low impedance and a range of gains for coupling of all equipment to the data
recording equipment.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory
        Micromotor Facilities (cont.)

6.   Micromotor B

The second stage of the test program involves the use of
Micromotor B for thrust measurements. The design of the thrust combustor will
be substantially less complicated than Micromotor A, in that the spectral mea-
surements and exhaust sample collection will not be required and water cooling
of the combustion chamber will be eliminated. However, the thrust stand planned
will carry much of the auxiliary equipment, such as the air/nitrogen storage
tank and heater, propellant tanks, valves, and lines. In this manner more
accurate thrust measurements can be made.

Design of the thrust stand and combustor will be initiated
later in the program. Experience with Micromotor A will provide necessary and
valuable information about the design requirements for Micromotor B.

III, Technical Discussion (cont.)

B. PHASE II: DETERMINATION OF COMBUSTION CHARACTERISTICS IN AIR
OF EXHAUST PRODUCTS OF PENTABORANE-HYDRAZINE SYSTEM

Phase II is concerned with the engine test evaluation of the air-augmented pentaborane-hydrazine system. Fifty-two tests are planned with Micromotor A and 23 tests are planned with Micromotor B. A wide range of test conditions will be investigated during the test phase, including:

1. Primary propellant mixture ratio--1.27, 0.9, and 0.6.

2. Primary chamber pressure--425 psia, 300 psia.

3. Air-to-propellant ratio--8:1, 16:1, and 40:1.

4. Secondary chamber pressure--200 psia, 50 psia.

5. Secondary air temperature--800°F, 1500°F.

Test measurements will include the following:

1. Propellant and air flow rates.

2. Air inlet temperature and pressure.

3. Pressure in the primary and secondary chambers.

4. Total thrust.

5. Percent conversion of boron and boron nitride to boron oxide(s) by collection and analysis of final exhaust products.

6. Optical measurements in the secondary chamber (gas-temperature determination is required, particle-temperature determination is desired).

Characteristic velocity, chamber temperature, and specific impulse will be calculated based on these test measurements.

The tentative test program planned for Micromotor A is outlined in Table I. Throughout the testing program, combustion efficiencies based on the calculation of characteristic velocity will be determined.

The initial tests will be directed primarily toward determining (1) the extent of combustion of boron and boron nitride in the combustor and (2) whether post-oxidation of these materials occurs. If conversion of these materials is not achieved, a larger secondary chamber will be installed.

III, B, Phase II: Determination of Combustion Characteristics in Air
of Exhaust Products of Pentaborane-Hydrazine System (cont.)

Temperature profile studies will be initiated using thermocouples
installed in the secondary chamber. In the placement of the thermocouples,
consideration will be given to the mixing pattern of the air and primary
exhaust streams, so that reliable interpretations can be made from the data.
Spectral measurements will be made also, to test the design of the optical
ports. A suitable window design is required in subsequent tests.

Emphasis in the experiments in the main body of the testing program
will be on studying the effects of the various operating parameters on the
performance characteristics of the air-augmented system. The efficiency of
boron and boron nitride conversion to the oxides, as indicated by c^* determina-
tions, will be substantiated by analyses of the combustion products of selected
runs.

The tentative test program using Micromotor B is presented in
Table II. These tests are devoted to the measurement of thrust under the
operating conditions previously studied for Micromotor A. From these data,
specific impulse calculations will be made. In addition to the thrust and
specific impulse determinations, the c^* values will be determined for compari-
son with the results obtained earlier in Micromotor A.

TABLE I

TENTATIVE TEST PROGRAM WITH MICROMOTOR A

Test No.	Secondary Air (or N_2) Temperature (°F)	Secondary Chamber Pressure (psia)	Air(or N_2)-to-Propellant Ratio	Primary Propellant Mixture Ratio	Remarks
		Test Parameters			
1	800	200	8/1	1.27	The medium-sized secondary chamber (1.9-in. dia and 14.0-in. length) will be used in Tests 1 through 6. The study of two particularly important factors (post-oxidation and conversion of B and BN to oxygenated species in the secondary chamber) will be emphasized in these first tests. Both phenomena will be studied by analysis of the solids in the secondary exhaust. If conversion does occur satisfactorily, the medium-sized secondary chamber will be used in the tests which follow. If conversion is not effected, the large-sized secondary chamber (2.9-in. dia and 60.0-in. length) will be used. A combustion efficiency based on c* will be determined for these runs. A major decision point will be reached at conclusion of Run 6.
2	800	200	16/1	1.27	
3	800	200	40/1	1.27	
4*	800	200	8/1	1.27	
5	800	200	8/1	1.27	
6	800	200	16/1	1.27	

TABLE I (cont.)

Test No.	Test Parameters — Secondary Air (or N₂) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N₂)-to-Propellant Ratio	Primary Propellant Mixture Ratio	Remarks
7	1500	50	8/1	1.27	These runs will again emphasize the study of post-oxidation and oxidation of boron species in secondary chamber. If oxidation of conversion of the boron species does occur satisfactorily, the medium-sized secondary chamber will continue to be used in the tests which follow. If not, the larger-sized chamber will be used. C* determinations will also be carried out. A major decision point will be reached at conclusion of Run 10.
8	1500	50	16/1	1.27	
9	1500	50	40/1	1.27	
10*	1500	50	8/1	1.27	
11	800	200	8/1	1.27	The objectives of Runs 11 through 16 are (1) to obtain a temperature profile along the longitudinal axis of the secondary chamber and (2) to check out spectral techniques for temperature measurements. Twelve thermocouples and a single pair of sapphire windows, i.e., one spectral analysis site, will be installed on secondary chamber for this purpose. C* determinations will also be carried out. A major decision point will be reached at conclusion of Run 16.
12	800	200	16/1	1.27	
13	800	200	40/1	1.27	
14*	800	200	8/1	1.27	
15	1500	50	8/1	1.27	
16	1500	50	16/1	1.27	

TABLE I (cont.)

Test No.	Secondary Air (or N₂) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N₂)-to-Propellant Ratio	Primary Propellant Mixture Ratio	Remarks
17	800	200	8/1	1.27	Emphasis in these runs will be placed on obtaining spectral data at three different locations of the secondary chamber; one site in the fore part of the chamber, a second intermediate site, and th_ third location in the aft part of the chamber. T.e three sites will be monitored simultaneously. Run 23 will be identical to Runs 17 and 18 except that nitrogen rather than air will be used. Runs 24 through 26 provide tests for the high Mach number simulation. Runs 27 through 29 provide tests for the low Mach number simulation plus a fuel-rich primary propellant combination. Spectral data will be obtained at each of three sites in each of these runs. C* determinations will be made for each run.
18	800	200	8/1	1.27	
19	800	200	16/1	1.27	
20	800	200	16/1	1.27	
21	800	200	40/1	1.27	
22	800	200	40/1	1.27	
23*	800	200	8/1	1.27	
24	1500	50	8/1	1.27	
25	1500	50	16/1	1.27	
26	1500	50	40/1	1.27	
27	800	200	8/1	0.9	
28	800	200	16/1	0.9	
29	800	200	40/1	0.9	

Test Parameters

TABLE I (cont.)

Test No.	Test Parameters				Remarks
	Secondary Air (or N$_2$) Temperature (°F)	Secondary Chamber Pressure (psia)	Air(or N$_2$)-to-Propellant Ratio	Primary Propellant Mixture Ratio	
30	800	200	8/1	0.6	The objective of this series of 11 runs, Runs 30 through 40, is to obtain performance data at propellant mixture ratios which are less than stoichiometric, e.g., MR = 0.9 and 0.6. Combustion efficiencies based on c* will be determined for each run.
31	800	200	16/1	0.6	
32	800	200	40/1	0.6	
33*	800	200	8/1	0.6	
34*	800	200	8/1	0.9	
35	1500	50	8/1	0.9	
36	1500	50	16/1	0.9	
37	1500	50	40/1	0.9	
38	800	200	8/1	Open	
39	800	200	16/1	Open	
40	800	200	40/1	Open	

TABLE I (cont.)

Test No.	Secondary Air (or N₂) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N₂)-to-Propellant Ratio	Primary Propellant Mixture Ratio	Remarks
		Test Parameters			
41	800	200	8/1	1.27	A primary nozzle having no diverging section will be used in Runs 41 through 46; the same secondary chamber used in the previous runs will be employed.
42	800	200	16/1	1.27	
43	800	200	40/1	1.27	This design may provide the best gas stream mixing and the highest primary exhaust temperature. The effect of these potentially beneficial parameters upon combustion efficiency (based on c*) is of interest.
44*	800	200	8/1	1.27	
45	800	200	16/1	0.6	
46	800	200	16/1	0.9	
47	800	200	8/1	1.27	Runs 47 through 52 will be conducted using the smallest of the three secondary chambers, i.e., the one having a 1.15-in. dia and 3.9-in. length. The results of this series of runs, as interpreted from combustion efficiency (c*), will provide useful design data for future programs.
48	800	200	16/1	1.27	
49	800	200	8/1	1.27	
50	800	200	16/1	1.27	
51	1500	50	8/1	1.27	
52	1500	50	16/1	1.27	

*Nitrogen will be used as the secondary gas in these runs.

TABLE II

TENTATIVE TEST PROGRAM WITH MICROMOTOR B

Test No.	Test Parameters				Remarks
	Secondary Air (or N$_2$) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N$_2$)-to-Propellant Ratio	Primary Propellant Mixture Ratio	
1	800	200	8/1	1.27	The primary objective of Runs 1 through 3 is to demonstrate whether the performance (based on c*) realized with Micromotor B is the same as with Micromotor A.
2	800	200	16/1	1.27	The experimental conditions associated with Runs 1 through 3 are identical with those of Runs 1 through 3 made with
3	800	200	40/1	1.27	Micromotor A. Micromotor B will be instrumented for thrust measurement and have the same design for the primary and secondary combustion chambers as Micromotor A. Micromotor B will also be checked out for thrust-measurement-use in these first runs.
4	800	200	8/1	1.27	The objective of these runs is to determine the thrust for the conditions given.
5	800	200	8/1	1.27	Test data will also provide c* values.
6*	800	200	8/1	1.27	
7	800	200	16/1	1.27	
8	800	200	16/1	1.27	
9	800	200	40/1	1.27	
10	800	200	40/1	1.27	

TABLE II (cont.)

Test No.	Secondary Air (or N₂) Temperature (°F)	Secondary Chamber Pressure (psia)	Air(or N₂)-to-Propellant Ratio	Primary Propellant Mixture Ratio	Remarks
11	1500	50	8/1	1.27	Runs 11 through 13 continue the pattern set by Runs 4 through 10. The secondary air temperature and the secondary chamber pressure are different for the two sets of runs, however. The same objectives are sought, i.e., thrust data primarily and c* data secondarily.
12	1500	50	16/1	1.27	
13	1500	50	40/1	1.27	
14	800	200	8/1	0.9	Runs 14 through 16 are the same as Runs 4 through 9 except that the propellant mixture ratio is lowered from 1.27 to 0.9.
15	800	200	16/1	0.9	
16	800	200	40/1	0.9	
17	800	200	8/1	0.6	Runs 17 through 19 are identical to Runs 4 through 9 except that the propellant mixture ratio is lowered from 1.27 to 0.6.
18	800	200	16/1	0.6	
19	800	200	40/1	0.6	

TABLE II (cont.)

Test No.	Test Parameters				Remarks
	Secondary Air (or N₂) Temperature (°F)	Secondary Chamber Pressure (psia)	Air(or N₂)-to-Propellant Ratio	Primary Propellant Mixture Ratio	
20	800	200	8/1	1.27	Runs 20 through 23 will be conducted using a primary nozzle having no diverging section. The same secondary chamber used in the previous runs will be employed. This design may provide the best gas stream mixing and the highest primary exhaust temperatures. Their effect upon thrust is of interest. These tests will be conducted only if the similar tests with Micromotor A, Tests 41 through 46, indicate that they are of interest. Other tests will be substituted if the non-expansion nozzle is deleterious.
21	800	200	16/1	1.27	
22	800	200	40/1	1.27	
23	1500	50	16/1	1.27	

*Nitrogen will be used as the secondary gas in these runs.

III, Technical Discussion (cont.)

C.   PHASE III: INTERPRETATION OF MICROMOTOR TEST RESULTS

This phase of the program is concerned with the development of a theoretical model of the combustion process or processes. Correlation between the various experimental parameters will be sought through theoretical chemical and physical considerations.

The combustion process which occurs in the primary chamber has been the subject of extensive study both at Aerojet and elsewhere (Reference 3). The theoretical reaction which yields the highest specific impulse and which is thermodynamically favored is represented by equation (1).

$$B_5H_9 + 2.5\ N_2H_4 = 5\ BN + 9.5\ H_2 \tag{1}$$
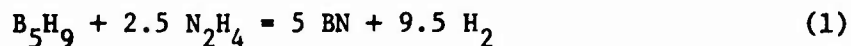
However, analyses of the combustion products, both gaseous and solid, and experimental performance tests indicate that this optimum process does not occur. Rather, the reactions which most satisfactorily account for the observed combustion products and performance are

$$B_5H_9 + 2N_2H_4 = 4\ BN + B + 8.5\ H_2 \tag{2}$$

$$0.5\ N_2H_4 = 0.5\ NH_3 + 0.25\ N_2 + 0.25\ H_2 \tag{3}$$
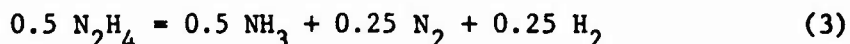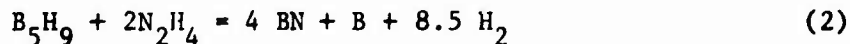
The secondary-combustion process in air will involve the combustion of both gaseous and solid, particulate material. This secondary process can be considered to occur in four distinct stages: (a) the mixing of air with the primary exhaust stream, (b) the ignition of the combustible gases, (c) the surface reaction of the particles, whereby their temperature is raised to ignition, and (d) the combustion of the boron nitride-boron in the vapor phase surrounding the particle or at the particle surface.

The mixing of the primary exhaust with air is accomplished by turbulent eddy diffusion followed by molecular diffusion. The turbulent eddy diffusion brings about the intermixing of the two streams on a sufficiently fine scale to permit the molecular diffusion to occur rapidly. Therefore, the efficiency of the mixing process is highly dependent on the physical configuration of the flowing streams and on the transport properties of the flows. Within the constraints of practical design considerations, the air inlet and primary exhaust ports have been designed to provide large velocity differences between the two streams and a large angle between their centerlines. These factors are considered to be especially important in the promotion of turbulence.

III, C, Phase III: Interpretation of Micromotor Test Results (cont.)

The combustible gases in the primary exhaust ignite as they mix
with the air. These gases, chiefly hydrogen and ammonia, have relatively
wide flammability limits and low ignition temperatures. Hence, the combustion
of these gases is expected to occur rapidly and completely.

A particle can be brought to its ignition temperature in two
different ways: (1) the transfer of heat from the gas surrounding the particle
or (2) by surface chemical reaction of the particle with the surrounding gas.
Heat transferred to the surface of the particle by either mechanism must
exceed the rate of dissipation of the energy from the surface.

Both particle size and concentration are factors in this heat
balance. A smaller particle has high surface-to-volume ratio, which results
in a high rate of heat production per unit volume and a low cooling rate.
When particle concentration is high, more of the heat radiated from a given
particle will be used to heat neighboring particles.

Surface oxidation of the particles can lead to the formation of a
protective oxide layer. If such a layer is formed, the result may be detri-
mental to particle ignition even though the particle temperature may be
increased. However, if the oxide is sufficiently volatile to vaporize and
expose unreacted surface, then ignition can be accomplished.

Similarly, the ultimate combustion of the particles is highly
dependent on the surface condition of the particle. If the active particle
surface is continually renewed by the volatilization of the oxide, then the
rate of combustion is controlled by the diffusion of oxygen to the surface
in the heterogeneous system. On the other hand, if the oxide does not vaporize
at a significant rate, then the combustion may be inhibited.

Homogeneous gas-phase reactions occur rapidly and efficiently;
consequently, in systems where the temperature is sufficiently high to vaporize
the material of the particle, as well as the combustion products, the maximum
rate of combustion is achieved.

The conditions which will be encountered in the secondary chamber
will vary over a wide range. The primary propellant ratio will be varied over
the range from pentaborane-rich to stoichiometric. Consequently, the boron
content of the solid exhaust will vary appreciably. Also, the air-to-propellant
ratio will be varied over a wide range, as will the air inlet temperature and
pressure, giving rise to large variations in chamber temperatures.

The variation in chamber conditions may result in significant
changes in the modes of ignition and combustion of the solid material.
Temperature profiles, studied both spectroscopically and with thermocouples,

III, C, Phase III: Interpretation of Micromotor Test Results(cont.)

and chemical analysis of the combustion products, will be of value in discerning the prevailing mechanisms. These observations, combined with the c* efficiencies and I_{sp} determinations will permit the establishment of the combustion model.

SECTION IV

FUTURE WORK

A. PHASE I: DESIGN, FABRICATION, AND INSTALLATION OF MICROMOTOR FACILITIES

1. Micromotor "A"

The preparation of the test bay and auxiliary facilities will be completed. The fabrication of the combustor components and the installation of the micromotor facilities will be completed.

2. Exhaust Sampling System

The design, fabrication, and installation of the exhaust sampling system, including the water-cooled ducts, and the dust-collection system, will be completed.

3. Spectral Equipment

The assembly and installation of the equipment for spectral temperature measurements will be completed.

4. Micromotor "B"

The design and fabrication of components of the thrust stand and combustor will be initiated as the design requirements are established.

B. PHASE II: DETERMINATION OF COMBUSTION CHARACTERISTICS IN AIR OF EXHAUST PRODUCTS OF PENTABORANE-HYDRAZINE SYSTEM

The testing program outlined in Table 1 is scheduled to commence on 18 September 1967 and the program outlined in Table 2 is scheduled to commence on 1 February 1968.

C. PHASE III: INTERPRETATION OF MICROMOTOR TEST RESULTS

This phase of the program is scheduled to commence on 18 September 1967, when the installation of Micromotor A has been completed and the testing program has been initiated.

REFERENCES

1. W. N. Harrison, Paper No. 1 of <u>Measurement of Thermal Radiation Properties of Solids</u>, J. C. Richmond, Editor of Symposium, Dayton, Ohio, September 1962.

2. S. F. Colucci and J. M. Adams, <u>Flame Temperature Measurement of Metalized Propellant</u> (U), Final Report on Contract AF 04(611)-10545, Report No. AFRPL-TR-66-203, September 1966 (Confidential).

3. <u>Proceedings of the Pentaborane-Hydrazine Combustion Conference</u>, Edwards Air Force Base, August 16-17, 1960.

APPENDIX

PROGRAM TEMP—A COMPUTATIONAL SCHEME IN
FORTRAN IV FOR DETERMINATION OF GAS AND
PARTICLE TEMPERATURE FROM SPECTROMETRIC DATA

I.   GENERAL DESCRIPTION

Program TEMP is a machine program written in Fortran IV language for use either with the IBM 360, 7094 or 1130 machines. Input data is placed on 80 column punched cards. Output is adaptable to 8-1/2 x 11 in. paper.

The program receives calibration data related to the spectral response of some sort of detector used for the spectrometric measurements. Detector constants (called "TUBE CONSTANT") are determined over any spectral range and signal strength, the number of total data points being limited to 100, at a maximum of 10 wavelengths.

From spectrometric data taken within the continuum of the flame and at specific spectrum line centers, the temperature of both the gas and particle cloud within the flame is calculated from Planck's Law.

II.   COMPUTATIONAL SCHEMES

The main program is divided into several computational schemes, identified by the comment card which corresponds to the following headings (refer to Table I).

TABLE I

```
      PROGRAM TEMP - A COMPUTATIONAL SCHEME IN FORTRAN IV        TEMP   1
C     FOR DETERMINATION OF GAS AND PARTICLE TEMPERATURES         TEMP   2
C     FROM SPECTROMETRIC DATA.                                   TEMP   3
C                                                                TEMP   4
C                                                                TEMP   5
      EXTERNAL TWF1                                              TEMP   6
      DIMENSION TA(15),FLA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),  TEMP   7
     1ELD(10)                                                    TEMP   8
      DIMENSION AK(100),E(100)                                   TEMP   9
      COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2                      TEMP  10
C                                                                TEMP  11
      AKTF(X3)=(A+B*(X3-EB))/GAIN                                TEMP  12
C                                                                TEMP  13
C     FORMAT STATEMENTS                                          TEMP  14
C                                                                TEMP  15
  100 FORMAT(I1)                                                 TEMP  16
  110 FORMAT(8F10.0)                                             TEMP  17
  120 FORMAT(4I5)                                                TEMP  18
  130 FORMAT(2F10.0,I10,5F10.0)                                  TEMP  19
  140 FORMAT( 27H0     MEAN PARTICLE VOLUME = E12.5,  7H CU CM   /  TEMP  20
     127H0   NUMBER CONCENTRATION = E12.5,11H PER CU CM  )       TEMP  21
  150 FORMAT(F10.0,I10)                                          TEMP  22
  160 FORMAT(34H0  EQUATION FOR TUBE CONSTANT AT F6.4, 9H MICRONS )  TEMP  23
  170 FORMAT( 16H0      K(E) = E12.5, 3H + E12.5, 6H (E - E12.5, 1H))  TEMP  24
  180 FORMAT(15H0   RUN TIME = F8.3,6H SECS )                    TEMP  25
  190 FORMAT( 37H0      WITH VARIANCE OF ESTIMATE = E12.5 /       TEMP  26
     137H       POPULATION VARIANCE = E12.5 /                    TEMP  27
     217H  FTEST = F7.3, 8H HAVING I3,14H DEG OF FRDM.  )         TEMP  28
  200 FORMAT(25H0  SOURCE TEMPERATURE = F9.3)                    TEMP  29
  210 FORMAT(E20.5,5F10.0)                                       TEMP  30
  220 FORMAT(4E20.5)                                             TFMP  31
  230 FORMAT(5F10.0,20X,I10)                                     TEMP  32
  240 FORMAT(22H0   FLAME THICKNESS = E12.5, 4H CM )             TEMP  33
  250 FORMAT(63H0          SCATTERING EFFECTS CONSIDERED----------TEMP  34
     1------ )                                                   TEMP  35
  260 FORMAT(22H0    PARTICLE EMISS. = F7.4,8H, REF = F7.4, 4H AT F6.4,  TEMP  36
     1 9H MICRONS / 22H   PARTICLE EMISS. = F7.4,8H, REF = F7.4,4H AT    TEMP  37
     2F6.4,9H MICRONS /21H   GAS EMISSIVITY = F7.4,4H AT F6.4,9H MICRON  TEMP  38
     3S )                                                        TEMP  39
  270 FORMAT(63H0     ****EFFECTIVE FLAME THICKNESS USED (MULT. SCATTERIN  TEMP  40
     1G)****       XNO*GS1*ST = E12.5  )                         TEMP  41
     /22H
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280 FORMAT(4E15.5/4E15.5)                                              TEMP 42
290 FORMAT(2H0 #PARTICLE TEMP. = F7.2, 1H,, GAS TEMP. = F7.2)          TEMP 43
300 FORMAT(64H0  ----  (ATTEN EFFECTS NEGLECTED---------               TEMP 44
     1-----)                                                            TEMP 45
310 FORMAT(22H)  PARTICLE EMISS. = F7.4,94H AT F6.4,9H MICRONS /22H    TEMP 46
     1 PARTICLE EMISS. = F7.4,15H, GAS EMISS. = F7.4,94H AT F6.4,9H MICROTEMP 47
     2NS      )                                                         TEMP 48
320 FORMAT(72H0-----                                                   TEMP 49
     1-----        /35H ----             CASE I2,35H---  TEMP 50
     2-----*                     )                                      TEMP 51
330 FORMAT(11H0     TIME = F8.3,5H SECS )                              TEMP 52
340 FORMAT(72H                                                         TEMP 53
     1                              /72H                                TEMP 54
     2                                     )                            TEMP 55
     3                                     )                            TEMP 56
350 FORMAT(5E10.5,F10.0)                                               TEMP 57
360 FORMAT(7F10.0,I10)                                                 TEMP 58
370 FORMAT( 32H0    TRANSVERSE - OPTICALLY THICK)                      TEMP 59
380 FORMAT( 32H0    TRANSVERSE - OPTICALLY THIN )                      TEMP 60
390 FORMAT(F8.1,3E21.5)                                                TEMP 61
400 FORMAT (3H0A 2F9.2,I4)                                             TEMP 62
410 FORMAT (3H0B 2F4.2,I4)                                             TEMP 63
420 FORMAT ( 25H0 I  ELD(I)      TW2(I)           )                    TEMP 64
430 FORMAT (I3,2X,F6.4,E14.5)                                          TEMP 65
440 FORMAT ( 3H0C 7F11.4/3E11.4/3E11.4/4E11.4 )                        TEMP 66
450 FORMAT(3H0D 5E12.5)                                                TEMP 67
460 FORMAT( 32H                                                        TEMP 68
C   READ DATA FOR TABLES OF EMISSIVITY VS. TEMP., WAVELENGTH           TEMP 69
    READ (5,120)J1,I1                                                  TEMP 70
    READ(5,110) (TA(I),I=1,J1)                                         TEMP 71
    READ(5,110)(ELA(I),I=1,I1)                                         TEMP 72
    READ (5,110) ((EPS1(I,J),I=1,I1),J=1,J1)                           TEMP 73
C                                                                       TEMP 74
C   I INDEX REFERS TO LAMBDA, J INDEX REFERS TO TEMPERATURE.           TEMP 75
C   EPSILONS SHOULD BE PUNCHED IN THE FOLLOWING MANNER -               TEMP 76
C   EPS(LAM(1),T(1)), EPS(LAM(2),T(1)),...EPS(LAM(I1),T(1)),           TEMP 77
C   EPS(LAM(1),T(2)), EPS(LAM(2),T(2))....                             TEMP 78
C                                                                       TEMP 79
C   READ WINDOW TRANSMISSIVITY (CLEAN)                                 TEMP 80
    READ (5,120),J2                                                    TEMP 81
    READ (5,110)(TW1(I),ELDB(I),I=1,J2)                                TEMP 82
                                                                        TEMP 83
    READ (5,130) C7,ELR,KR,ERX,CSRV                                    TEMP 84
                                                                        TEMP 85
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C     C2 = THE CONSTANT IN THE PLANCK RELATION.                          TEMP  86
C     ELK = THE WAVELENGTH AT WHICH BRIGHTNESS TEMP. IS MEASURED.        TEMP  87
C     KO = NO. OF ALLOWED ITERATIONS IN DETER. OF TRUE TEMPERATURE.      TEMP  88
C     ERR = ALLOWED REL. ERROR IN TRUE TEMP. OF REF. SOURCE             TEMP  89
C                                                                        TEMP  90
      READ (5,110) EL1,EL2                                               TEMP  91
  470 READ (5,340)                                                       TEMP  92
      JJJ=1                                                              TEMP  93
C                                                                        TEMP  94
C     PRINT HEADING                                                      TEMP  95
C                                                                        TEMP  96
      WRITE (6,340)                                                      TEMP  97
      READ (5,100) IND1                                                  TEMP  98
C                                                                        TEMP  99
C     INDICATOR CODE                                                     TEMP 100
C                                                                        TEMP 101
C            DESCRIPTION                                                 TEMP 102
C     IND1                                                               TEMP 103
C      1     READ NEW CALIBRATION DATA, CALC. AND PRINT TABLES, CALC.    TEMP 104
C            AND PRINT TEMPERATURES                                      TEMP 105
C      2     CONTINUE TO READ AND PRINT CALIBRATION AT VARIOUS LAMBDA    TEMP 106
C      3     READ ONLY PRE-, POSTRUN CALIBRATION, CALC., PRINT TEMP.     TEMP 107
C      4     PRINT EVERYTHING, INCLUDING CHECKOUT VALUES                 TEMP 108
C      5     CALL EXIT                                                   TEMP 109
C     IND                                                                TEMP 110
C      0     READ MORE TEMPERATURE DATA CARDS                            TEMP 111
C      1     READ NEW CASE, SAME EMISSIVITY TABLES                       TEMP 112
C     IND3                                                               TEMP 113
C      1     BRIGHTNESS TEMPERATURE IN DEGREES FAHRENHEIT                TEMP 114
C      2     BRIGHTNESS TEMPERATURE IN DEGREES CENTIGRADE                TEMP 115
C      3     BRIGHTNESS TEMPERATURE IN DEGREES KELVIN                    TEMP 116
      READ (5,350) VBAR,GA1,GS1,GA2,GS2,CHI                             TEMP 117
      GO TO (480,480,690,480,870),IND1                                   TEMP 118
C     ********************************************************TEMP        TEMP 119
C     CALCULATION OF DETECTOR CONSTANTS                                  TEMP 120
C                                                                        TEMP 121
C     READ WAVELENGTH VALUE FOR PHOTOTUBE CALIBRATION POINTS             TEMP 122
  480 READ(5,130)ELC                                                     TEMP 123
      J5=1                                                               TEMP 124
      IND4=1                                                             TEMP 125
      GAIN=1.0                                                           TEMP 126
      I=1                                                                TEMP 127
C                                                                        TEMP 128
C     READ DATA FROM PRELIMINARY PHOTOTUBE CALIBRATION. THIS CALIBRATION TEMP 129
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C    ACCOMPLISHED WITH REFERENCE LIGHT SOURCE POSITIONED CLOSE ENOUGH     TEMP 130
C    TO SPECTROMETER TO GIVE OUTPUT EMF GREATER THAN ANY EMF GENERATED    TEMP 131
C    DURING THE RUN.                                                      TEMP 132
C    ONE OR MORE EMF VALUE REQUIRED FOR EACH BRIGHTNESS TEMP AT THE       TEMP 133
C    WAVELENGTH READ IN ABOVE. ONE BLANK CARD REQUIRED TO READ IN NEW     TEMP 134
C    BRIGHTNESS TEMP. TWO BLANK CARDS REQUIRED AT END OF THIS DATA.       TEMP 135
C    TB = BRIGHTNESS TEMPERATURE.                                         TEMP 136
490  READ (5,150)TB,IND3                                                  TEMP 137
                                                                          TEMP 138
     IF(TB)630,630,500                                                    TEMP 139
500  GO TO (510,520,530),IND3                                            TEMP 140
510  TX=TB                                                                TEMP 141
     TB=(TB+459.6)/1.8                                                    TEMP 142
     GO TO 540                                                            TEMP 143
520  TX=(TB+273.12)*1.8-459.6                                             TEMP 144
     TB=TB+273.12                                                         TEMP 145
     GO TO 540                                                            TEMP 146
530  TX=T3*1.8-459.6                                                      TEMP 147
540  T1=TR                                                                TEMP 148
     K1=0                                                                 TEMP 149
550  T2=C2/(FLR*ALOG(1.0+EPS(FLR,T1)*( EXP(C2/(ELR*TR))-1.0)))            TEMP 150
     GO TO (570,570,560,570,560,570),K1                                   TEMP 151
560  WRITE (6,400)T1,T2,K1                                                TEMP 152
570  K1=K1+1                                                              TEMP 153
     IF(ABS((T1-T2)/T1)-ERR)600,600,580                                   TEMP 154
580  IF(K1-K0)590,600,600                                                 TEMP 155
590  T1=T2                                                                TEMP 156
     GO TO 550                                                            TEMP 157
600  TS=T2                                                                TEMP 158
     GO TO (610,700),IND4                                                 TEMP 159
                                                                          TEMP 160
C    READ EMFS, E1, AT GIVEN TB. EQUATION CALCULATED                      TEMP 161
                                                                          TEMP 162
610  READ (5,110) F1                                                      TEMP 163
     IF(E1)490,490,620                                                    TEMP 164
620  E(IJ)=E1                                                             TEMP 165
     AN(IJ)=EPS(ELC,TS)*TWF1(ELC)**2*RI(ELC,TS)/E1                        TEMP 166
     I=I+1                                                                TEMP 167
     GO TO 610                                                            TEMP 168
                                                                          TEMP 169
C    REINITIALIZE                                                         TEMP 170
630  JJ=I-1                                                               TEMP 171
     EN=JJ                                                                TEMP 172
     GXY=0.0                                                              TEMP 173
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```
      SY=0.0                                                        TEMP 174
      SX=0.0                                                        TEMP 175
      SX2=0.0                                                       TEMP 176
      DO 640 I=1,JJ                                                 TEMP 177
      SXY=SXY+AK(I)*E(I)                                            TEMP 178
      SY=SY+AK(I)                                                   TEMP 179
      SX2=SX2+E(I)**2                                               TEMP 180
640   SX=SX+E(I)                                                    TEMP 181
      A=SY/EN                                                       TEMP 182
      EB=SX/EN                                                      TEMP 183
      IF(EN*SX2-SX**2)660,650,660                                   TEMP 184
650   B=0.0                                                         TEMP 185
      GO TO 670                                                     TEMP 186
660   B=(EN*SXY-SX*SY)/(EN*SX2-SX**2)                               TEMP 187
670   SP2=0.0                                                       TEMP 188
      SE2=0.0                                                       TEMP 189
      DO 680 I=1,JJ                                                 TEMP 190
      SE2=SE2+((A+B*(E(I)-EB)-AK(I))**2)/(EN-2.)                    TEMP 191
680   SP2=SP2+((AK(I)-A)**2)/(EN-1.)                                TEMP 192
      FTEST=SP2/SE2                                                 TEMP 193
C                                                                   TEMP 194
C     PRINT TUBE CONSTANT EQUATION                                  TEMP 195
      WRITE (6,160) ELC                                             TEMP 196
      WRITE (6,170) A,B,EB                                          TEMP 197
      WRITE (6,190) SE2,SP2,FTEST,JJ                                TEMP 198
      GO TO (690,480,690,690,690),IND1                              TEMP 199
C     READ REFERENCE SOURCE CONDITION PRIOR TO RUN. ESTABLISH       TEMP 200
C     GAIN CHANGE FROM CALIBRATION CONDITION                        TEMP 201
690   IND4=2                                                        TEMP 202
      GO TO 490                                                     TEMP 203
700   SUME1=0.0                                                     TEMP 204
      I=0                                                           TEMP 205
710   READ(5,110) E1                                                TEMP 206
      IF (E1) 730,730,720                                           TEMP 207
720   SUME1=SUME1+E1                                                TEMP 208
      I=I+1                                                         TEMP 209
      EN=I                                                          TEMP 210
      GO TO 710                                                     TEMP 211
730   AVE1=SUME1/EN                                                 TEMP 212
      GAIN=AVE1*AKTF(AVE1)/(RI(ELC,TS)*EPS(ELC,TS)*TWF1(ELC)**2)    TEMP 213
      WRITE(6,460) GAIN                                             TEMP 214
C     ********************************************************      TEMP 215
C     CALCULATION OF REFERENCE SOURCE AND WINDOW CONDITIONS DURING RUN TEMP 216
C                                                                   TEMP 217
```

```
C     READ REFERENCE POINT TO ESTABLISH REF. SOURCE TEMP DURING RUN      TEMP 218
740   READ(5,130) E10P,ELD                                              TEMP 219
      T1=3000.                                                          TEMP 220
      K2=0                                                              TEMP 221
750   T2=C2/(FLP*ALOG(1.+FPS(FLP,T1)/(FLP**5.*F10P*AKTF(F10P))))        TEMP 222
      GO TO (770,770,770,760,770),IND1                                  TEMP 223
C                                                                       TEMP 224
C     CHECKOUT PRINT                                                    TEMP 225
760   WRITE (6,410) T1,T2,K2                                            TEMP 226
770   IF(ABS((T2-T1)/T1)-ERR)800,800,780                               TEMP 227
780   K2=K2+1                                                           TEMP 228
      IF(K2-K0)790,800,800                                             TEMP 229
790   T1=T2                                                             TEMP 230
      GO TO 750                                                         TEMP 231
800   TS=T2                                                             TEMP 232
C                                                                       TEMP 233
C     PRINT SOURCE TEMPERATURE DURING RUN                               TEMP 234
      WRITE (6,200) TS                                                  TEMP 235
C                                                                       TEMP 236
C     READ POST-FIRE REFERENCE POINTS TO ESTABLISH CHANGE OF TRANSMISS- TEMP 237
C     IVITY DURING RUN, TR = RUN TIME                                   TEMP 238
C     TW2(I)=TRANSMISSIVITY AT END OF RUN AT WAVELENGTH ELPP(I).        TEMP 239
C     REINITIALIZE                                                      TEMP 240
      I=1                                                               TEMP 241
      READ (5,110) TR                                                   TEMP 242
      WRITE (6,180) TR                                                  TEMP 243
810   READ (5,110)E10PP,ELPP                                            TEMP 244
C                                                                       TEMP 245
      IF(E10PP)870,870,820                                              TEMP 246
820   TW2(I)=(F10PP*AKTF(F10PP)/(FPS(FLPP,TS)*RI(FLPP,TS)))**.5         TEMP 247
      ELD(I)=ELPP                                                       TEMP 248
      GO TO (830,530,860,830,830),IND1                                  TEMP 249
830   GO TO (840,850),J5                                                TEMP 250
840   WRITE (6,420)                                                     TEMP 251
      J5=2                                                              TEMP 252
850   TTT=TW2(I)                                                        TEMP 253
C                                                                       TEMP 254
C     PRINT POST FIRE TRANSMISSIVITY                                    TEMP 255
      WRITE(6,430) I,ELPP,TTT                                           TEMP 256
860   I=I+1                                                             TEMP 257
      GO TO 810                                                         TEMP 258
C     **********************************************************TEMP    TEMP 259
C     CALCULATION OF GAS AND PARTICLE CLOUD TEMPERATURES AND            TEMP 260
C     SPECTRAL EMITTANCE                                                TEMP 261
```

```
C
  870 READ (5,360) TI,EL1,E12,E21,E22,RHOL,RHOG,IND                  TEMP 262
      XNO=CHI*RHOG/((CHI*RHOG+(1.-CHI)*RHOL)*VBAR)                    TEMP 263
      WRITE (6,140) VBAR,XNO                                          TEMP 264
      IND2=IND+1                                                      TEMP 265
      CALL TRANS (TI,TR,TWF1,EL1,EL2,TAU1,TAU2)                       TEMP 266
C                                                                     TEMP 267
C     ST = THICKNESS OF THE FLAME, CM.                               TEMP 268
C                                                                     TEMP 269
      ST=-(ALOG((EL1*AKTF(EL1)-E12*AKTF(E12))/(TAU1**2.*EPS(EL1,TS)*  TEMP 270
     1RI(EL1,TS))))/(XNO*(GA1+GS1))                                   TEMP 271
      COMP=XNO*GS1*ST                                                 TEMP 272
      Z=ST                                                            TEMP 273
      WRITE (6,320) JJJ                                              TEMP 274
      IND6=1                                                          TEMP 275
      WRITE (6,330) TI                                                TEMP 276
      WRITE (6,250)                                                   TEMP 277
  880 WRITE (6,240) ST                                                TEMP 278
C                                                                     TEMP 279
C     CALCULATE EMISSIVITY OF PARTICLE CLOUD                          TEMP 280
C                                                                     TEMP 281
      EPSP1=1.-EXP(-XNO*GA1*ST)                                       TEMP 282
      REFP1=1.-EXP(-XNO*GS1*ST)                                       TEMP 283
C                                                                     TEMP 284
C     CALCULATE PARTICLE TEMPERATURE                                 TEMP 285
      TP=C2/(EL1*ALOG(1.+TAU1*EPSP1/(EL1**5.*E12*AKTF(E12))))         TEMP 286
      EPSP2=1.-EXP(-XNO*GA2*ST)                                       TEMP 287
      REFP2=1.-EXP(-XNO*GS2*ST)                                       TEMP 288
C                                                                     TEMP 289
C     CALCULATE SPECTRAL ABSORPTION COEFFICIENTS.                    TEMP 290
      GAG=-ALOG((E21*AKTF(E21)-E22*AKTF(E22))/(TAU1**2*EPS(EL2,TS)*RI(ELTEMP 291
     12,TS)))/Z-XNO*(GA2+GS2)                                         TEMP 292
      EPSG=1.-EXP(-GAG*ST)                                            TEMP 293
C                                                                     TEMP 294
C     CALCULATE GAS TEMPERATURE                                      TEMP 295
      ABB=1.-(1.-EPSP2)*(1.-EPSG)                                     TEMP 296
      CEE2=XNO*CA2+GAG                                                TEMP 297
      CEE3=(XNO*GA2/GAG)*RI(EL2,TP)                                   TEMP 298
      CEE=1.+1./(EL2**5.*(E22*AKTF(E22)*CEE2/(GAG*TAU2*ABB)-CEE3))    TEMP 299
      TG=C2/(EL2*ALOG(CEE))                                           TEMP 300
C                                                                     TEMP 301
C     PRINT ALL TEMPERATURES                                         TEMP 302
      WRITE (6,260) EPSP1,REFP1,EL1,EPSP2,REFP2,EL2,EPSG,EL2          TEMP 303
      WRITE(6,370)                                                    TEMP 304
      WRITE (6,290) TP,TG                                            TEMP 305
```

```
      TP=C2/(EL1*ALOG(1.+TAU1*GA1*(1.-EXP(-XNO*(GA1+GS1)*ST))/(FL1**5.*      TEMP 306
     1EL2*AKTF(E12)*(GA1+GS1))))                                             TEMP 307
      ABB=1.-(1.-EPSG)*(1.-EPSP2)*(1.-REFP2)                                 TEMP 308
      CEE2=XNO*(GA2+GS2)+GAG                                                 TEMP 309
      CEE=1.+1./(EL2**5.*(E22*AKTF(E22)*CEE2/(GAG*TAU2*ABB)-CEE3))           TEMP 310
      TG=C2/(EL2*ALOG(CEE))                                                  TEMP 311
      WRITE (6,380)                                                          TEMP 312
      WRITE (6,290) TP,TG                                                    TEMP 313
      GO TO (900,900,890,9001,IND1                                          TEMP 314
  890 WRITE (6,280) GA1,GA2,GS1,GS2,GAG,CEE2,CEE3,CEE                        TEMP 315
    C                                                                        TEMP 316
  900 GO TO (910,920),IND6                                                   TEMP 317
  910 IND6=2                                                                 TEMP 318
      ST=COMP*ST                                                            TEMP 319
      WRITE (6,270) COMP                                                     TEMP 320
      GO TO 880                                                             TEMP 321
    C CALCULATE VARIABLES FOR SAME DATA, NEGLECTING SCATTERING              TEMP 322
  920 EPSP1=1.0+(E12*AKTF(E12)-E11*AKTF(E11))/(TAU1**2.*EPS(EL1,TS)          TEMP 323
     1*RI(EL1,TS))                                                          TEMP 324
      EPSP2=EPSP1*(GA2/GA1)                                                 TEMP 325
      T2=C2/(EL1*ALOG(1.+EPSP1*TAU1/(EL1**5.*E12*AKTF(E12))))               TEMP 326
      EPSG=1.0-(E21*AKTF(E21)-E22*AKTF(E22))/((1.-EPSP2)*TAU2**2.           TEMP 327
     1*EPS(EL2,TS)*RI(EL2,TS))                                              TEMP 328
      GAP=-ALOG(1.-EPSP1)                                                   TEMP 329
      GAG=-ALOG(1.-EPSG)                                                    TEMP 330
      GO TO (940,940,940,930,940),IND1                                      TEMP 331
  930 DD=EPS(EL1,TS)                                                        TEMP 332
      FF=RI(EL1,TS)                                                         TEMP 333
      GG=T*FL1(EL1)                                                         TEMP 334
      WRITE (6,450) DD,FF,GG                                                TEMP 335
      WRITE (6,440) T1,TR,EL1,E11,E12,EL2,E21,E22,EL21,TAU1,TAU2,GAP,GAG     TEMP 336
  940 ABB=1.-(1.-EPSG)*(1.-EPSP1)                                           TEMP 337
      CEE2=GAP+GAG                                                          TEMP 338
      CEE3=(GAP/GAG)*RI(EL2,TP)                                             TEMP 339
      CEE=1.+1./(FL2**5.*(E22*AKTF(E22)*CEE2/(GAG*TAU2*ABB)-CEE3))          TEMP 340
      TG=C2/(EL2*ALOG(CEE))                                                 TEMP 341
      ARITF (6,300)                                                         TEMP 342
      WRITE (6,310) FPSP1,FL1,EPSP2,EPSG,EL2                                TEMP 343
      WRITE (6,290) TP,TS                                                   TEMP 344
      JJJ=JJ+1                                                              TEMP 345
      GO TO (870,870),IND2                                                  TEMP 346
  950 END                                                                   TEMP 347
    C SUBROUTINES OR FUNCTIONS USED                                         TEMP 348
    C RI(WAVELENGTH,TEMP.)=THE PLANCK FUNCTION                              TEMP 349
```

```
C    EPS(WAVELENGTH,TEMP.),THE REFERENCE LIGHT SOURCE EMISSIVITY       TEMP 350
C    TWF(WAVELENGTH),THE TRANSMISSIVITY OF THE CLEAN WINDOW            TEMP 351
C    TRANS, A SUBROUTINE TO CALCULATE TIME-DEPENDENT WINDOW TRANSMISS. TEMP 352
     FUNCTION RI(EL,T)                                                 RI   1
     DIMENSION TA(15),ELA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),     RI   2
    1ELD(10)                                                           RI   3
     COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2                             RI   4
     X=C2/(EL*T)                                                       RI   5
     IF(X-170.)110,110,100                                             RI   6
 100 RI=0.0                                                            RI   7
     RETURN                                                            RI   8
 110 RI=1.0/(EL**5.*(EXP(C2/(EL*T))-1.0))                              RI   9
     RETURN                                                            RI  10
     END                                                               RI  11
     FUNCTION EPS(EL, T)                                               EPS  1
     DIMENSION TA(15),ELA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),     EPS  2
    1ELD(10)                                                           EPS  3
     COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2                             EPS  4
     N=2                                                               EPS  5
     M=2                                                               EPS  6
 120 IF (EL-ELA(M)) 150,150,130                                        EPS  7
 130 M=M+1                                                             EPS  8
 140 GO TO 120                                                         EPS  9
 150 IF (T-TA(N)) 180,180,160                                          EPS 10
 160 N=N+1                                                             EPS 11
 170 GO TO 150                                                         EPS 12
 180 EPS1=EPSI(M-1,N-1)+((T-TA(N-1))/(TA(N)-TA(N-1)))*(EPSI(M-1,N)-     EPS 13
    1EPSI(M-1,N-1))                                                    EPS 14
 190 EPS2=EPSI(M,N-1)+((T-TA(N-1))/(TA(N)-TA(N-1)))*(EPSI(M,N)-EPSI     EPS 15
    1(M,N-1))                                                          EPS 16
 200 EPS=EPS1+((EL-ELA(M-1))/(ELA(M)-ELA(M-1)))*(EPS2-EPS1)            EPS 17
     RETURN                                                            EPS 18
     END                                                               EPS 19
     FUNCTION TWF1(EL)                                                 TWF1 1
     DIMENSION TA(15),ELA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),     TWF1 2
    1ELD(10)                                                           TWF1 3
     COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2                             TWF1 4
     M=2                                                               TWF1 5
 100 IF(EL-ELR(M))120,120,110                                          TWF1 6
 110 M=M+1                                                             TWF1 7
     GO TO 100                                                         TWF1 8
 120 TWF1= TW1(M-1)+(EL-FLR(M-1))*(TW1(M)-TW1(M-1))/(ELB(M)-ELR(M-1))   TWF1 9
     RETURN                                                            TWF1 10
     END                                                               TWF1 11
```

```
      SUBROUTINE TRANS (T,S,J,A,B,X,Y)                           TRANS  1
      DIMENSION TA(15),FLA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10), TRANS 2
     1ELD(10)                                                    TRANS  3
      COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2                      TRANS  4
      V=A                                                        TRANS  5
      J=1                                                        TRANS  6
 100  M=2                                                        TRANS  7
 110  IF(V-FLD(M))130,130,120                                    TRANS  8
 120  M=M+1                                                      TRANS  9
      GO TO 110                                                  TRANS 10
 130  TW2T = TW2(M-1)+(V-ELD(M-1, *(TW2(M)-TW2(M-1))/(ELD(M)-ELD(M-1)) TRANS 11
      AA=(1./S )*(U(V)/TW2T -1.)                                 TRANS 12
      W= U(V)/(1.+AA*T)                                          TRANS 13
      GO TO (140,150),J                                          TRANS 14
 140  X=W                                                        TRANS 15
      V=B                                                        TRANS 16
      J=2                                                        TRANS 17
      GO TO 100                                                  TRANS 18
 150  Y=W                                                        TRANS 19
      RETURN                                                     TRANS 20
      END                                                        TRANS 21
```

II, Computational Schemes (cont.)

A.   CALCULATION OF DETECTOR CONSTANTS

After having read into storage the emissivity tables for the
reference source being used in the calibration, the program will then accept
data which relates signal strength (e.g., galvanometer deflection, inches) to
reference source intensity (e.g., brightness temperature). After having
calculated the detector constants which relate measured signal strength to
radiance (or temperature), the program prints out an equation for the relation-
ship together with statistical indicators by which to assess the validity of
the relationship.

B.   CALCULATION OF REFERENCE SOURCE AND WINDOW CONDITIONS DURING RUN

The reference source temperature is determined from the measured
signal from the reference source just prior to flame introduction. Data on
reference source intensity just after flame extinguishment is also introduced
as input at this point in the routine, together with the run time. To account
for any spectral nonuniformity in window transmissivity, the post-test data
can include up to 10 wavelength data, each being associated with a corresponding
source intensity. Any transient change in window transmissivity or reference
source radiance is accounted for subsequently in the calculations of tempera-
ture from the spectrometric data, with the assumption that such changes occurred
linearly with time between the pre- and post   data points (i.e., during the
"run time").

C.   CALCULATION OF GAS AND PARTICLE CLOUD TEMPERATURES AND SPECTRAL
    EMITTANCE

The spectrometric data, in the form of galvanometer deflections,
are introduced here. Data on gas and condensed phase density are used
together with previously stored data on particle absorption and scattering
cross sections to calculate the particle number density (or concentration) and
other physical properties of the particle cloud as required. If no particulates
are present in the flame, the mass fraction of particles, CHI, is set equal
to zero on the input.

Several computational options are used to calculate temperatures.
The first of these treats the problem of radiation scattering by the particle
cloud for the "optically thin"* condition. This treatment is valid for most
common flames having particulate mass fractions up to 0.4 together with a
thickness up to 7 centimeters. When conditions on condensed phase mass fraction
or thickness simultaneously exceed these values, the results may be invalid.

---

*This refers to optical characteristic of the cloud for scattering of
 radiation along the "line of sight;" this case is shown directly under
 "SCATTERING EFFECTS CONSIDERED," Table II.

II, C, Calculation of Gas and Particle Cloud Temperatures and Spectral
     Emittance (cont.)

At this condition on optical depth in a direction parallel to the optical axis,
two conditions on transverse optical thickness are considered. In the first
of these, termed the "TRANSVERSE-OPTICALLY THICK" case, the temperatures are
computed for the condition where scattering losses from the flame radiation
equal scattering gains, within the optical path. This condition is most
frequently valid. In the second condition, termed "TRANSVERSE-OPTICALLY THIN"
(see Table II), the results are based on the assumption that there is a net
scattering loss of radiation from the flame within the optical path, either
because the flame's transverse dimension is extremely small or because there
is extreme thermal disequilibrium. In both of the above cases, it is assumed
that all the radiation from the reference source, scattered out of the
optical path, is permanently lost.

TABLE II

SAMPLE OUTPUT, PROGRAM TEMP

RUN NUMBER N-2, NITROGEN, TIME APPROXIMATE
   SODIUM SOLUTION USED TO COAT WALLS ON DOWNSTREAM END OF MIX CHAMBER

   EQUATION FOR TUBE CONSTANT AT 0.5890 MICRONS

       $K(E) = 0.73433E-03 + -0.43587E-04 (F - 0.11233E 01)$

       WITH VARIANCE OF ESTIMATE = 0.49151E-10
             POPULATION VARIANCE = 0.41460E-09
       FTEST = 8.435 HAVING 12 DEG OF FRDM.
       GAIN RATIO, RUN/CAL. = 1.00369

   SOURCE TEMPERATURE = 2792.472

   RUN TIME = 55.000 SECS

   I ELD(I)   TW2(I)
   1 0.5880   0.96636E 00
   2 0.5890   0.96705E 00
   3 0.5900   0.96067E 00

   MEAN PARTICLE VOLUME = 0.10000E-11 CU CM

   NUMBER CONCENTRATION = 0.26666E 02 PER CU CM

   -----------------------------------CASE 1-----------------------------------

   TIME = 0.000 SECS

   ------------------SCATTERING EFFECTS CONSIDERED------------------

   FLAME THICKNESS = 0.12406E 06 CM

   PARTICLE EMISS. = 0.0033, REF = 0.0325 AT 0.5880 MICRONS
   PARTICLE EMISS. = 0.0033, REF = 0.0325 AT 0.5890 MICRONS
   GAS EMISSIVITY = 0.3031 AT 0.5890 MICRONS

   TRANSVERSE - OPTICALLY THICK

   *PARTICLE TEMP. 2828.01, GAS TEMP. = 2817.15

   TRANSVERSE - OPTICALLY THIN

   *PARTICLE TEMP. = 2833.41, GAS TEMP. = 2822.24

[handwritten annotation] computed from EIOP, ELP all temperatures in °K

[handwritten annotation] where particle effects are important, this qty must agree with actual thickness.

[handwritten annotation] considered to be most valid under normal conditions

TABLE II (cont.)

*****EFFECTIVE FLAME THICKNESS USED (MULT. SCATTERING)*****
        XNO*GS1*ST =   0.33084E-01

FLAME THICKNESS =   0.41047E 04 CM

PARTICLE EMISS. = 0.0001, REF =   0.0010 AT 0.5880 MICRONS
PARTICLE EMISS. = 0.0001, REF =   0.0010 AT 0.5890 MICRONS
GAS EMISSIVITY =   0.0118 AT 0.5890 MICRONS

TRANSVERSE - OPTICALLY THICK

*PARTICLE TEMP. = 4660.34, GAS TEMP. = 4491.25

TRANSVERSE - OPTICALLY THIN

*PARTICLE TEMP. = 4660.87, GAS TEMP. = 4491.71

----------------SCATTERING EFFECTS NEGLECTED----------------

PARTICLE EMISS. = 0.0357 AT 0.5880 MICRONS
PARTICLE EMISS. = 0.0357, GAS EMISS. = 0.3031 AT 0.5890 MICRONS

*PARTICLE TEMP. = 2217.68, GAS TEMP. = 2822.18

valid where no particles
are present in flow stream.

II, C, Calculation of Gas and Particle Cloud Temperatures and Spectral
Emittance (cont.)

The above computations are repeated, using an effective flame
thickness to account for multiple scattering. The validity of this treatment
has not been verified but it is used to serve as a basis of comparison.

Lastly, the data is reduced and temperatures calculated with the
assumption that there is no scattering of radiation by the particles. This
case leads to an accurate determination of temperature where the particles
are pure absorbers or where there are no particles.

Under conditions ordinarily encountered in flames and small
rocket motors, either the output directly under the heading "SCATTERING
EFFECTS CONSIDERED. . . TRANSVERSE-OPTICALLY THICK" or under the heading
"SCATTERING EFFECTS NEGLECTED," (Table II) will be most valid.

II, Computational Schemes (cont.)

D. SUBROUTINES OR FUNCTIONS USED

Subordinate to the main program deck are four subroutines which are used by the main program to perform intermediate calculations and interpolate tabulated information. They are described in the following paragraphs.

1. Function RI(EL, T)

This subroutine calculates the value of the Planck function:

$$R_i(\lambda, T) = \frac{1}{\lambda^5 \quad \exp\left(\frac{C_2}{\lambda T}\right) - 1}$$

2. Function EPS (EL, T)

This subroutine is used to perform the interpolation of the tabulated reference light source emissivity, $\varepsilon(\lambda, T)$.

3. Function TWF1 (EL)

This subroutine interpolates tabulated pre-run window transmissivity data to obtain the window transmissivity at any specified wavelength.

4. Subroutine TRANS (T,C,U,A,B,X,T)

This subroutine calculates the window transmissivity at the specified time, based upon pre- and post-test transmissivity data. It is assumed that window deposits build up linearly with time.

III. INPUT INFORMATION

The variables which must be included as input and the required format is shown in Table I. The following list of nomenclature gives a description of each of the input variables, in the order in which they must be read in.

Set Number	Input Variable	Description [Format]
1	*J1, I1	Indicates number of temperature, wavelength data points to be used in reference light source emissivity tables. [2I5.]
1a	*TA(I)	Temperature data point corresponding to identically indexed emissivity data point, °K. Maximum number of points is 15. [8F10.0]
1b	*ELA(I)	Wavelength data point corresponding to identically indexed emissivity data point, micron. Maximum number points is 40. [8F10.0]
1c	*EPSI(I,J)	Reference source emissivity data point at the ith value of wavelength and the jth value of temperature. Emissivity data is read in the order $\varepsilon(\lambda_1,T_1)$, $\varepsilon(\lambda_2,T_2)$, $\varepsilon(\lambda_3,T_1)$ . . . $\varepsilon(\lambda_{11},T_1)$, $\varepsilon(\lambda_1,T_2)$, $\varepsilon(\lambda_2,T_2)$ . . . $\varepsilon(\lambda_2,T_2)$ . . . $\varepsilon(\lambda_{I1},T_{J1})$. Maximum number of points is 600. [8F10.0]
2	*J2	Indicates number of pre-run window transmissivity data to be read in. [I5]
2a	*TW1(I)	Pre-run window transmissivity at the ith wavelength.
	ELB(I)	The ith wavelength value for TW1(I), microns. [8F10.0]
3	*C2	The Planck constant, 14388 °K. [F10.0]
	ELR	The wavelength in microns at which brightness temperature measurements are taken, usually 0.653 . [F10.0]
	KLO	Number of allowed interations in the iterations determination of source temperature from measured brightness temperature. Usually taken as 10. [I10]

---

*Indicates new input card required at the start of this set. All input variables after each * are placed on same card up to 8.

III, Input Information (cont.)

Set Number	Input Variable	Description [Format]
	ERR	Allowed relative error in the true source temperature calculated from the measured brightness temperature, usually taken as 0.000001. [F10.0]
	CONV	Not used in Program 660300.
4	*EL1	Wavelength at which continuum spectral radiance is measured, microns. [F10.0]
	EL2	Wavelength at spectrum line center where radiance is measured, microns. [F10.0]
5	*Heading	Placed on three cards. First column of each card should contain a blank. Any arrangement of letters and numbers may be used in the first 72 columns of three cards. [72H]
6	*IND1	Indicator [I1]
	=1	means: Read detector calibration data at one wavelength, calculate and print temperatures.
	=2	Continue to read calibration data and print tables of detector constants at several wavelengths.
	=3	Suppress printing of detector calibration data, calculate and print temperatures.
	=4	Print all data, including internal checkout sequences. Used only when output error cannot be found.
	=5	Call exit.
7	*VBAR	Number mean particle volume pertaining to particles present within the flow stream, cm^3. [E10.5]
	GA1	Average absorption cross section of particles for radiation of wavelength EL1, cm^2. [E10.5]
	GS1	Average scattering cross section for radiation of wavelength EL1, cm^2. [E10.5]
	GA2	Same as GA1, except for wavelength EL2.
	GS2	Same as GS1, except for wavelength EL2.
	CHI	Mass fraction of particulate matter in flame, gms solids/gms total. [F10.0]

III, Input Information (cont.)

Set Number	Input Variable	Description [Format]
8	*ELC	The wavelength at which the pre-run reference light source calibration is performed, microns. [F10.0]
9	*TB	Brightness temperature at which the first set of detector signals (E1) is recorded, at the gain setting used during calibration. [F10.0]
	IND3	Indicator, placed in the 20th column of the same card with TB.
	= 1	TB is in degrees Fahrenheit
	= 2	TB is in degrees Centigrade
	= 3	TB is in degrees Kelvin
10	*E1	The recorded detector signal corresponding to TB. Any number of E1 cards can be read in for each value of TB, but no more than 100 values of E1 can be read in for all TB with the same value of ELC. [F10.0]
	*	<u>A blank card placed here</u> indicates that a new value of TB (Set #9) is to be read in followed by the corresponding E1 cards (Set 10). <u>Two blank cards placed here</u> indicates that the detector constant correlation equation is to be calculated and printed. The input proceeds as follows: If IND1=2, the machine will read in a new value of ELC (Set #8) and repeat. If IND1=1, the machine will proceed to the next input card shown below (Set #11).
11	*TB	Brightness temperature at which the detector signal (E1) is recorded at the gain setting used during the run. One only. [F10.0]
	IND3	Indicator (see Set #9)
12	*E1	The recorded detector signal corresponding to TB. Any number of E1 cards can be read in. The arithmetic average of all E1's will be computed and used to determine the gain change between the calibration and run conditions. [F10.0]

III, Input Information (cont.)

Set Number	Input Variable	Description [Format]
	*	A blank card placed here indicates that all the E1 cards have been read in; the machine will calculate the gain change, print, and proceed to the next input card shown below (Set #13).
13	*E10P	The measured level of detector signal with the reference light source on in the condition used during the run. This value is used to calculate the true source temperature during the run, and serves as the reference on which all the temperature measurements are based. [F10.0]
	ELP	The wavelength to which E10P corresponds, microns. [F10.0]
14	*TR	The total run time, seconds [F10.0]
15	#E10PP	The post-test equivalent of E10P. [F10.0]
	ELPP	The wavelength to which E10PP corresponds.
		Note: Although only one card containing both E10P and ELP can be read, as many as 10 values of E10PP and ELPP can be read, with both E10PP and ELPP on one card [2F10.0], since the post-test window transmissivity may be strongly spectrally dependent.
	*	A blank card placed here signifies that all E10PP have been read in. The machine proceeds to the next input card shown below, set #16.
16	*TI	The time in seconds from the start of the run. This serves as the basis on which window transmissivity is calculated. If no change in window transmissivity occurs, the value of TI is unimportant. [F10.0]
	E11	Measured signal with reference source on, at EL1. [F10.0]
	E12	Measured signal with reference source off, at EL1. [F10.0]

III, Input Information (cont.)

Set Number	Input Variable	Description [Format]
	E21	Measured signal with reference source on, at EL2. [F10.0]
	E22	Measured signal with reference source off, at EL2. [F10.0]
	RHOL	Density of condensed phase, gms/cm^3. [F10.0]
	RHOG	Density of gas phase, gms/cm^3. [F10.0]
	IND	Indicator code placed in 80th column.
	= 0	(blank) Read new data card
	= 1	Read new entire case, starting with set number 5, the heading.

UNCLASSIFIED
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Aerojet-General Corporation P.O. Box 15847 Sacramento, Calif.	Unclassified
	2b GROUP

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4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

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5 AUTHOR(S) *(Last name, first name, initial)*

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10 AVAILABILITY/LIMITATION NOTICES

11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY
	Rocket Propulsion Laboratory Air Force Systems Command Edwards, California

13 ABSTRACT

The design of the first of two liquid micromotors, has been completed. This micromotor will be used for the determination of characteristic velocity, chamber temperature and analysis of the exhaust products. The preparation of the test sight has begun and the fabrication and installation of the micromotor and auxiliary equipment has been initiated.

A tentative test plan has been developed for the study of the combustion characteristics in air of the pentaborane-hydrazine system.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pentaborane-Hydrazine						
Air Augmentation						
Micromotor						
Spectral Comparator Pyrometer						

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